

Constraints on the neutrino mass and the cosmological constant from large scale structure observations

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Abstract. The observational data on the large scale structure (LSS) of the Universe are used to establish the upper limit on the neutrino content marginalized over all other cosmological parameters within the class of adiabatic inflationary models. It is shown that the upper 2σ limit on the neutrino content can be expressed in the form $\Omega_\nu h^2 / N_\nu^{0.64} \leq 0.042$ or, via the neutrino mass, $m_\nu \leq 4.0\text{eV}$.

INTRODUCTION

In the light of recent data on the matter content in the Universe ($0.25 \leq \Omega_m \leq 0.5$) coming from cosmological observations and lower limit on the neutrino contribution ($\Omega_\nu \geq 0.001$) which follows from the Super-Kamiokande experiment, the question whether cosmology still allows neutrino mass of a few eV is of interest for Cosmology as well as Particle Physics. Relict massive neutrinos as collisionless particles with substantial velocities suppress the power spectrum of matter density perturbations below of free-streaming scale, which depends mainly on the neutrino mass, the Hubble constant and time. Hence, the comparison of the growth of mass fluctuations on these scales can be translated into an upper limit for the neutrino mass. From the Ly- α forest in quasar spectra in together with a conservative implementation of other cosmological constraints a limit of $m_\nu \leq 5.5\text{eV}$ at 95% C.L. has been reported [6]. The problem of this determination is that the damping of small scale power due to neutrinos can be imitated by variations of other cosmological parameters like the spectral index n_s , the cosmological constant Λ , spatial curvature Ω_k , the Hubble parameter h ($\equiv H_0/(100\text{km/s/Mpc})$) and the baryon content Ω_b . Therefore, Ω_ν (or m_ν) must be determined simultaneously with all these parameters using a wide range scale of cosmological observations. Such investigations show also that mixed dark matter models with cosmological constant (ΛMDM) can explain virtually all cosmological measurements [14]. The goal of this paper is to determine more carefully the upper limit on the neutrino content and its rest mass

in the framework of Λ MDM models.

We determine the parameters of the cosmological model which matches observational data on the large scale structure of the Universe best and, marginalizing over all other parameters, we determine the upper limit for the neutrino content and the neutrino mass. We restrict ourselves to the sub-class of models without tensor mode and neglect early reionization.

EXPERIMENTAL DATA SET AND METHOD

Our approach is based on the comparison of the observational data on the structure of the Universe over a wide range of scales with theoretical predictions from the power spectrum of small (linear) density fluctuations. The form of the spectrum strongly depends on the cosmological parameters Ω_m , Ω_b , Ω_ν , N_ν , h and n_s . If the amplitude on a given scale is fixed by some observational data then predictions for observations on all other scales can be calculated and compared with observational data. Minimizing quadratic differences between the theoretical and observational values divided by the observational errors, χ^2 , determines the best-fit values of the above mentioned cosmological parameters. We use the following observational data set:

1. The location $\tilde{\ell}_p = 197 \pm 6$ and amplitude $\tilde{A}_p = 69 \pm 8 \mu\text{K}$ of the first acoustic peak in the angular power spectrum of the CMB temperature fluctuations deduced from CMB map obtained in the Boomerang experiment [2] (these data are sensitive to the amplitude and form of the initial power spectrum in the range $\approx 200h^{-1}\text{Mpc}$);
2. The power spectrum of density fluctuations of Abell-ACO clusters ($\tilde{P}_{A+ACO}(k_j)$) obtained from their space distribution by [16] (scale range $10 - 100h^{-1}\text{Mpc}$);
3. The constraint for the amplitude of the fluctuation power spectrum on $\approx 10h^{-1}\text{Mpc}$ scale derived from a recent optical determination of the mass function of nearby galaxy clusters [10];
4. The constraint for the amplitude of the fluctuation power spectrum on $\approx 10h^{-1}\text{Mpc}$ scale derived from the observed evolution of the galaxy cluster X-ray temperature distribution function between $z = 0.05$ and $z = 0.32$ [17];
5. The constraint for the amplitude of the fluctuation power spectrum on $\approx 10h^{-1}\text{Mpc}$ scale derived from the existence of three very massive clusters of galaxies observed so far at $z > 0.5$ [1];
6. The constraint on the amplitude of the linear power spectrum of density fluctuations in our vicinity obtained from the study of bulk flows of galaxies in sphere of radius $50h^{-1}\text{Mpc}$ $\tilde{V}_{50} = (375 \pm 85)\text{km/s}$ [13];
7. The constraint for the amplitude of the fluctuation power spectrum on $0.1 - 1h^{-1}\text{Mpc}$ scale and $z = 3$ derived from the Ly- α absorption lines seen in quasar spectra [11];
8. The constraints for the amplitude and inclination of the initial power spectrum on $\approx 1h^{-1}\text{Mpc}$ scale and $z = 2.5$ scale derived from the Ly- α forest of quasar

absorption lines [5];

9. Results from direct measurements of the Hubble constant $\tilde{h} = 0.65 \pm 0.10$ which is a compromise between by different groups;

10. The nucleosynthesis constraint on the baryon density derived from a observational content of inter galactic deuterium, $\Omega_b h^2 = 0.019 \pm 0.0024$ (95% C.L.) [4].

One of the main ingredients for the solution of our search problem is a reasonably fast and accurate determination of the linear transfer function for dark matter clustering which depends on the cosmological parameters. We use accurate analytical approximations of the MDM transfer function $T(k; z)$ depending on the parameters Ω_m , Ω_b , Ω_ν , N_ν and h given in Ref. [9]. The linear power spectrum of matter density fluctuations is $P(k; z) = A_s k^{n_s} T^2(k; z) D_1^2(z)/D_1^2(0)$, where A_s is the normalization constant for scalar perturbations and $D_1(z)$ is the linear growth factor. We normalize the spectra to the 4-year COBE data which determine the amplitude of density perturbation at horizon scale, δ_h [3]. Therefore, each model will match the COBE data by construction. The normalization constant A_s is then given by $A_s = 2\pi^2 \delta_h^2 (3000 \text{Mpc}/h)^{3+n_s}$.

The Abell-ACO power spectrum is related to the matter power spectrum at $z = 0$ by the cluster biasing parameter b_{cl} : $P_{A+ACO}(k) = b_{cl}^2 P(k; 0)$. We assume scale-independent linear bias as free parameter the best-fit value of which will be determined together with the other cosmological parameters.

The dependence of the position and amplitude of the first acoustic peak in the CMB power spectrum on cosmological parameters n_s , h , Ω_b , Ω_{cdm} and Ω_Λ can be determined using an analytical approximation given in [8] which has been extended to models with non-zero curvature ($\Omega_k \equiv 1 - \Omega_m - \Omega_\Lambda \neq 0$) in [7]. Its accuracy in the parameter range considered is better then 5%.

The theoretical values of the other experimental constraints are calculated as described in [14]. There one can also find some tests of our method.

RESULTS AND DISCUSSION

The determination of the parameters Ω_m , Ω_Λ , Ω_ν , N_ν , Ω_b , h , n_s and b_{cl} by the Levenberg-Marquardt χ^2 minimization method is realized as follows: we vary the set of parameters Ω_m , Ω_Λ , Ω_ν , Ω_b , h , n_s and b_{cl} with fixed N_ν (= number of massive neutrino species) and find the minimum of χ^2 . Since N_ν is discrete we repeat this procedure for $N_\nu=1, 2$, and 3. The lowest of the three minima is the minimum of χ^2 for the complete set of free parameters. We have seven continuous free parameters. The formal number of data points is 24 but, as it was shown in [14], the 13 points of the cluster power spectrum can be described by just 3 degrees of freedom, so that the maximal number of truly independent measurements is 14. Therefore, the number of degrees of freedom for our search procedure is $N_F = N_{\text{exp}} - N_{\text{par}} = 7$. The model with one sort of massive neutrinos provides the best fit to the data, $\chi_{\text{min}}^2 = 5.9$. Its parameters are following $\Omega_m = 0.37^{+0.25}_{-0.15}$, $\Omega_\Lambda = 0.69^{+0.15}_{-0.20}$, $\Omega_\nu =$

$0.03^{+0.07}_{-0.03}$, $N_\nu = 1$, $\Omega_b = 0.037^{+0.033}_{-0.018}$, $n_s = 1.02^{+0.09}_{-0.10}$, $h = 0.71^{+0.22}_{-0.19}$, $b_{cl} = 2.4^{+0.7}_{-0.7}$. The errors are obtained by maximizing the (Gaussian) 68% confidence contours over all other parameters.

However, there is only a marginal difference in χ^2_{min} for $N_\nu = 1, 2, 3$. With the given accuracy of the data we cannot conclude whether massive neutrinos are present at all, and if yes what number of degrees of freedom is favored. We summarize, that the considered observational data on LSS of the Universe can be explained by a Λ MDM inflationary model with approximately a scale invariant spectrum of scalar perturbations and small positive curvature, $\Omega_k = -0.06$. It is interesting to note that the values of the fundamental cosmological parameters Ω_m , Ω_Λ and Ω_k determined by these observations of large scale structure match the SNIa test $\Omega_m - 0.75\Omega_\Lambda = -0.25 \pm 0.125$ [15] very well. Models with vanishing Λ are outside of marginalized 3σ contour of the best-fit model with $N_\nu = 1$ determined by the LSS observational characteristics used here even without the SNIa constraint (Fig. 1a). For models with $N_\nu = 2$ and $N_\nu = 3$ contours are a bit wider, so models with vanishing Λ are outside the marginalized 2σ contour for arbitrary N_ν .

Results change only slightly if instead of the Boomerang data we use Boomerang+MAXIMA-1. Hence, we can conclude that the LSS observational characteristics together with the Boomerang (+MAXIMA-1) data on the first acoustic peak already rule out zero- Λ models at more than 95% C.L. and actually demand a cosmological constant in the same bulk part as direct measurements. We consider this a non-trivial consistency check!

The neutrino matter density $\Omega_\nu = 0.03$ corresponds to a neutrino mass of $m_\nu = 94\Omega_\nu h^2 \approx 1.4$ eV but is compatible with 0 within 1σ . A Λ CDM model ($\Omega_\nu = 0$) is within the 1σ contour of the best-fit Λ MDM model.

To derive an upper limit for neutrino content and its rest mass, we first determine the marginalized 1σ , 2σ and 3σ upper limits for Ω_ν for different values of N_ν . Using the best-fit value for h at given Ω_ν , we then obtain the a corresponding upper limit for the neutrino mass, $m_\nu = 94\Omega_\nu h^2 / N_\nu$. The results are presented in Table 1 and Figure 1. For more species of massive neutrino the upper limit for Ω_ν is somewhat higher but m_ν is still lower for each C.L. The upper limit for Ω_ν raises with the confidence level as expected. But the upper limit for the mass grows only very little due to the reduction of the best-fit value for h . The upper limit for the combination $\Omega_\nu h^2 / N_\nu^{0.64}$ is approximately constant for all numbers of species and confidence levels. The observational data set used here establishes an upper limit for the massive neutrino content of the universe which can be expressed in the form $\Omega_\nu h^2 / N_\nu^{0.64} \leq 0.042$ at 2σ confidence level. The corresponding upper limit on the neutrino mass $m_\nu \leq 4\text{eV}$ is lower than the value obtained by [6].

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TABLE 1. Upper limits for the neutrino content and mass (in eV) at different confidence levels.

N_ν	1 σ C.L.		2 σ C.L.		3 σ C.L.	
	Ω_ν	m_ν	Ω_ν	m_ν	Ω_ν	m_ν
1	0.10	3.65	0.13	3.96	0.18	4.04
2	0.15	2.79	0.21	3.06	0.29	3.35
3	0.20	2.40	0.27	2.67	0.35	2.78

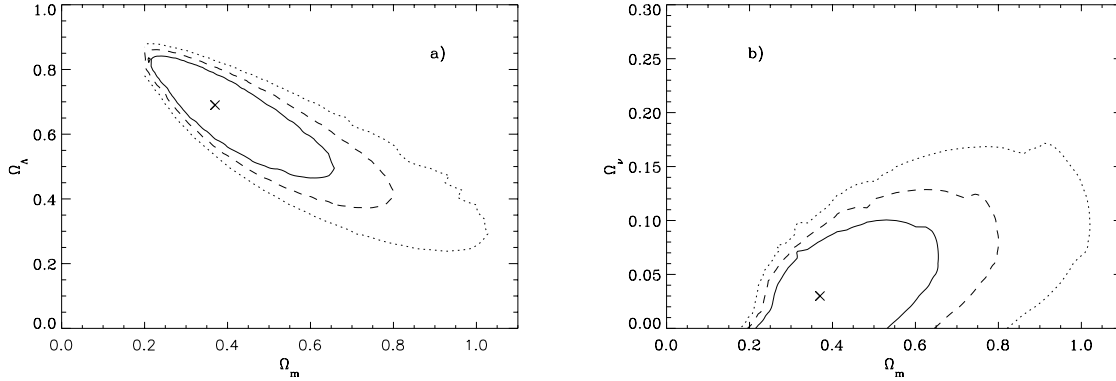


FIGURE 1. Likelihood contours (solid line - 68.3%, dashed - 95.4%, dotted - 99.73%) of Λ CDM with $N_\nu = 1$ in the $\Omega_m - \Omega_\Lambda$ (a) and $\Omega_m - \Omega_\nu$ (b) planes marginalized over all other parameters.

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